Guidelines for Extracting Well Proximity Effect Instance Parameters

Revision History

Revision	Date	Authors	Comments
1.0	9-Dec-05	M. Basel, J. Xi, J. Watts, P. Humphries, K. Su, S. Moinian	First draft of CMC well proximity guidelines
1.1	12-Dec-05	M. Basel	Updated figures, added corner equations
1.2	14-Dec-05	M. Basel	Simplify section usage, reformat
1.3	16-Dec-05	M. Basel	Grammar fixes
1.4	1-Mar-06	M. Basel	Fixed problems with device drawings. Fixed figure and equation labels. Re-wrote pre-layout section.
1.5	2-Mar-06	M. Basel, S. Moinian, J. Watts	Updated corner equations. Added reference.
1.6	7-Mar-06	M. Basel, S. Moinian	Corrections to corner equations. Expanded corner explanation.
1.6	10-Mar-06	M. Basel, J. Watts	Added averaging for multi-fingered devices

Review History

Revision	Date	Attendees
2.0	10-Mar-06	CMC meeting, Austin Texas, 10 March, 2006

Sections

Equations

Figures

1 Introduction to well proximity effects

Retrograde well profiles have several key advantages for highly scaled bulk complementary metal oxide semiconductor (CMOS) technology. With the advent of high-energy implanters and reduced thermal cycle processing, it has become possible to provide a relatively heavily doped deep nwell and pwell without affecting the critical device-related doping at the surface. The deep well implants provide a low resistance path, suppress parasitic bipolar gain for latchup protection, and can also improve soft error rate and noise isolation. A deeply buried layer is also key to forming triple-well structures for isolated-well NMOSFETs. However, deep buried layers can affect devices located near the mask edge. Some of the ions scattered from the edge of the photoresist are implanted in the silicon surface near the mask edge, altering the threshold voltage [1] of those devices by upwards of 100mV. This effect is known as the well proximity effect (abbreviated as WPE).

Currently the BSIM4 model incorporates well proximity effect on threshold voltage, mobility, and the body effect. Eventually the new PSP transistor model selected by the council will incorporate this effect as well.

2 The well proximity effect model

Experimental analysis shows that the well proximity effect is a strong function of the distance of the FET from the mask edge, and electrical quantities influenced by it follow the same geometrical trend. A phenomenological model based on these findings has been developed by modifying some parameters in the BSIM model. Note that the following equations have no impact on the iteration time because there are no voltage-controlled components in them.

Threshold voltage, mobility and the body effect are all affected by the well proximity effect, their new equations can be described as:

$$Vth0 = Vth0_{org} + \mathrm{KVTH0WE} \cdot \left(\mathrm{SCA} + \mathrm{WEB} \cdot \mathrm{SCB} + \mathrm{WEC} \cdot \mathrm{SCC}\right)$$

$$K2 = K2_{org} + \mathrm{K2WE} \cdot \left(\mathrm{SCA} + \mathrm{WEB} \cdot \mathrm{SCB} + \mathrm{WEC} \cdot \mathrm{SCC}\right)$$

$$\mu_{eff} = \mu_{eff,org} \cdot \left(1 + \mathrm{KU0WE} \cdot \left(\mathrm{SCA} + \mathrm{WEB} \cdot \mathrm{SCB} + \mathrm{WEC} \cdot \mathrm{SCC}\right)\right)$$

Equation 1 Calculation of threshold voltage, mobility and body effect

where SCA, SCB, SCC are instance parameters that represent the integral of the first/ second/third distribution functions for scattered well dopants.

The equations presented here are curve fit expressions that have been found to fit measured data reasonably well. In many instances, only the SCA term (Equation 2) is necessary to provide a reasonable level of accuracy. In these equations:

> n = Number of projections of the well edge along the width of the devices for which SC (the distance between gate edge and well edge) is constant.
> m = Number of projections of the well edge along the length of the devices for which SC (the distance between gate edge and well edge) is constant. Note that the count for this starts from n+1 and not 1.

For relatively large distances, the effect falls off roughly as the distance squared, as modeled by the SCA term. For technologies whose design rules do not allow well edges close to an active area, only SCA is needed and WEB and WEC may be set to zero. The resist height effects how far the dopant ions scatter, therefore the SCB and SCC equations have a maximum value at intermediate distances, allowing for fine tuning of the model to match observed data for a wide variety of processes (along with the WEB and WEC variables).

Closed form solutions to the integrals may be found with the result shown in Equation 3. Details on the corner terms will be discussed later in this document.

$$\mathrm{SCA} = \left\{ \begin{array}{l} \dfrac{1}{W_{drawn} \cdot L_{drawn}} \\ \cdot \left[\sum_{i=1}^{n} \left(W_i \cdot \int_{SC_i}^{SC_i + L_{drawn}} f_A(u)du \right) + \sum_{i=n+1}^{n+m} \left(L_i \cdot \int_{SC_i}^{SC_i + W_{drawn}} f_A(u)du \right) + corners\_A \right] \end{array} \right\}$$

$$f_A(u) = \frac{SC_{ref}{}^2}{u^2}$$

$$\mathrm{SCB} = \left\{ \begin{array}{l} \dfrac{1}{W_{drawn} \cdot L_{drawn}} \\ \cdot \left[\sum_{i=1}^{n} \left(W_i \cdot \int_{SC_i}^{SC_i + L_{drawn}} f_B(u)du \right) + \sum_{i=n+1}^{n+m} \left(L_i \cdot \int_{SC_i}^{SC_i + W_{drawn}} f_B(u)du \right) + corners\_B \right] \end{array} \right\}$$

$$f_B(u) = \frac{u}{SC_{ref}} \exp(-10 \cdot \frac{u}{SC_{ref}})$$

$$\mathrm{SCC} = \left\{ \begin{array}{l} \dfrac{1}{W_{drawn} \cdot L_{drawn}} \\ \cdot \left[\sum_{i=1}^{n} \left(W_i \cdot \int_{SC_i}^{SC_i + L_{drawn}} f_C(u)du \right) + \sum_{i=n+1}^{n+m} \left(L_i \cdot \int_{SC_i}^{SC_i + W_{drawn}} f_C(u)du \right) + corners\_C \right] \end{array} \right\}$$

$$f_C(u) = \frac{u}{SC_{ref}} \exp(-20 \cdot \frac{u}{SC_{ref}})$$

Equation 2 Integral forms for instance parameters SCA, SCB, and SCC

$$\mathrm{SCA}=\frac{1}{W_{drawn}L_{drawn}}\left[\begin{array}{l} SC_{ref}{}^{2}\sum_{i=1}^{n}\left(W_{i}\left(\frac{1}{SC_{i}}-\frac{1}{SC_{i}+L_{drawn}}\right)\right)+ \\ SC_{ref}{}^{2}\sum_{i=n+1}^{n+m}\left(L_{i}\left(\frac{1}{SC_{i}}-\frac{1}{SC_{i}+W_{drawn}}\right)\right)+corners\_A \end{array}\right]$$

$$\mathrm{SCB}=\frac{1}{W_{drawn}L_{drawn}}\left[\begin{array}{l} \sum_{i=1}^{n}\left(W_{i}\left(\begin{array}{l} SC_{ref}\left(\frac{SC_{i}}{10}+\frac{SC_{ref}}{100}\right)\exp(-10\frac{SC_{i}}{SC_{ref}})- \\ SC_{ref}\left(\frac{SC_{i}+L_{drawn}}{10}+\frac{SC_{ref}}{100}\right)\exp(-10\frac{SC_{i}+L_{drawn}}{SC_{ref}}) \end{array}\right)\right)+ \\ \sum_{i=n+1}^{n+m}\left(L_{i}\left(\begin{array}{l} SC_{ref}\left(\frac{SC_{i}}{10}+\frac{SC_{ref}}{100}\right)\exp(-10\frac{SC_{i}}{SC_{ref}})- \\ SC_{ref}\left(\frac{SC_{i}+W_{drawn}}{10}+\frac{SC_{ref}}{100}\right)\exp(-10\frac{SC_{i}+W_{drawn}}{SC_{ref}}) \end{array}\right)\right)+corners\_B \end{array}\right]$$

$$\mathrm{SCC}=\frac{1}{W_{drawn}L_{drawn}}\left[\begin{array}{l} \sum_{i=1}^{n}\left(W_{i}\left(\begin{array}{l} SC_{ref}\left(\frac{SC_{i}}{20}+\frac{SC_{ref}}{400}\right)\exp(-20\frac{SC_{i}}{SC_{ref}})- \\ SC_{ref}\left(\frac{SC_{i}+L_{drawn}}{20}+\frac{SC_{ref}}{400}\right)\exp(-20\frac{SC_{i}+L_{drawn}}{SC_{ref}}) \end{array}\right)\right)+ \\ \sum_{i=n+1}^{n+m}\left(L_{i}\left(\begin{array}{l} SC_{ref}\left(\frac{SC_{i}}{20}+\frac{SC_{ref}}{400}\right)\exp(-20\frac{SC_{i}}{SC_{ref}})- \\ SC_{ref}\left(\frac{SC_{i}+W_{drawn}}{20}+\frac{SC_{ref}}{400}\right)\exp(-20\frac{SC_{i}+W_{drawn}}{SC_{ref}}) \end{array}\right)\right)+corners\_C \end{array}\right]$$

Equation 3 Closed form solutions for SCA, SCB, and SCC

3 Extraction of post-layout instance parameters

The well proximity effect is highly physical in nature, requiring the extraction of numerous physical parameters. The basic approach is to find the well edges that coincide with active region and therefore have a good probability of contributing scattered ions into the device region. The following sections describe the recommended methodology for determining the lengths, widths, and spacings (SC_i, W_i and L_i) for various situations.

3.1 Extraction of simple MOSFETs

Figure 1 shows the typical layout of a MOSFET with an irregularly shaped well. The measurement for SC_i, W_i and L_i may be found by projecting the edges of the channel toward the well edges as shown. Note that even though the active area of the device is a simple rectangle, it gets fractured into smaller pieces due to the irregular well perimeter. The original width (W) of the device is therefore fractured into two separate widths (W1 and W2) along the left edge, for example. The distance from these two new widths are SC1 and SC2, respectively.

In the equations, n is the number of segments projecting along the L direction and m is the number of segments in the projecting the W direction.

The effect of scattering from a well edge drops off rapidly as the distance from the edge to the device channel region increases. Searching edges more than a few channel lengths from a device will not significantly improve accuracy while potentially slowing down layout extraction times. The figure also illustrates the use of a maximum search distance with the Smax parameter. Any edges outside of Smax will be ignored, only edges within the search distance will be included in the calculations for SCA, etc. Note that for the Smax distance shown, only the following parameters would be included in the calculations;

- SC1, W1
- SC5, L5
- SC3, W3
- SC7, L7

The other parameters are outside of the Smax 'box' and would not be included in the well proximity calculations.

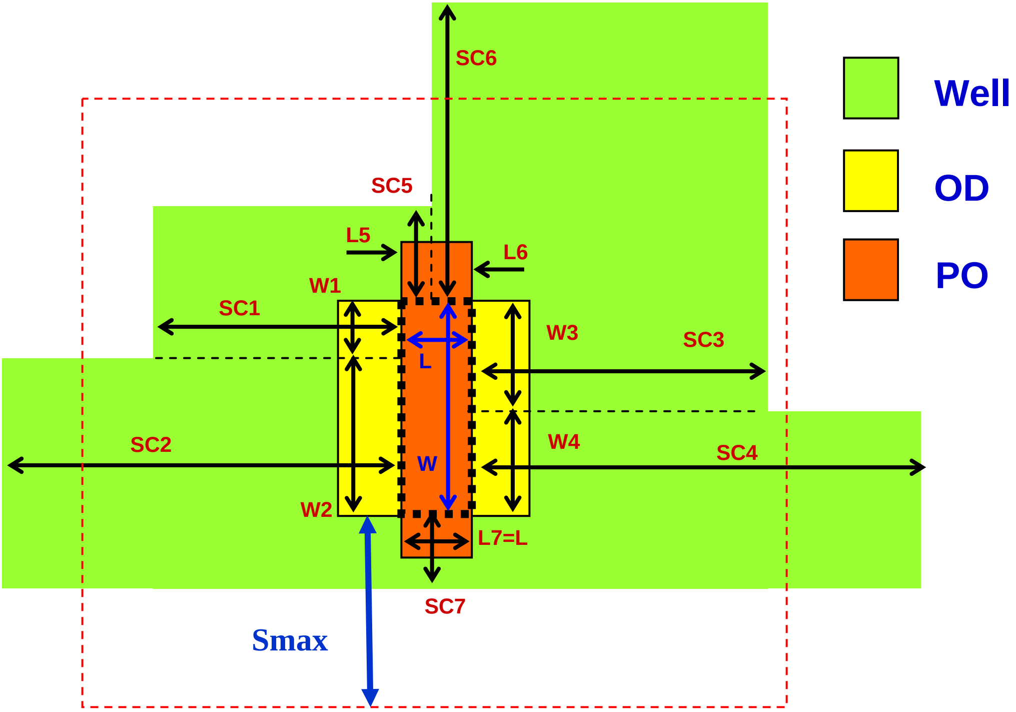

Figure 1 Typical MOSFET layout showing WPE parameters and maximum search distance

3.2 Dealing with multiple MOSFETs within maximum search distance

Only the nearest well edges need be accounted for when calculating the well proximity parameters SCA, SCB and SCC. An example of this is shown in Figure 2 where the following can be said about the five transistors:

- NFET1 is affected only by edges A, G, and L
- PFET1 is affected only by edges A, B, I, and H
- NFET2 is affected only by edges B, C, and D
- PFET2 is affected only by edges D, E, H, and J
- NFET3 is affected only by edge E

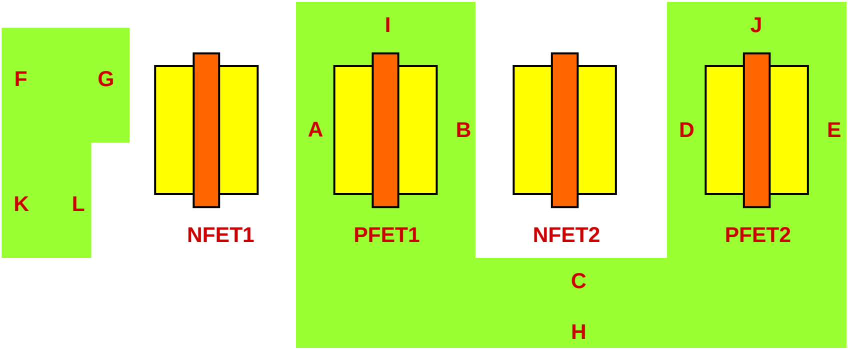

Figure 2 Accounting for well edges

3.3 Handling non-coincident well and active edges (e.g. 'corner' effects)

The resist edge scatters dopant ions in all directions, not just perpendicular to the well edges. Therefore the scattered ions seen by any point in the active region is an integration of the distance function over all visible edges. For well edges that do not have a common run length with the active region, their effect is significantly less than for edges that run the entire length of the active region. The corner equations attempt to capture this situation, but since the effect is less than for edges with common run lengths, the search distance for corners is correspondingly less. The effect of well corners on threshold voltage, etc. may not be significant, in which case the corner terms (Equation 4) may be neglected. Again, this is process dependent and the decision to include this effect should be verified for any particular process. For corners, a search distance of 1/2 Smax is usually sufficient.

An example showing well corners is shown in Figure 3. There are five corners total in this example, but corners 3 and 4 fall outside of the Smax search distance and are therefore neglected.

One method for incorporating the impact of scattered dopants from well corners outside the projection regions can be calculated (see Figure 3) as:

$$corner\_A = \sum_{i=m+1}^{m+k} \left(\frac{L_{drawn}}{2} \int_{SCX_i+SCY_i}^{SCX_i+SCY_i+W_{drawn}} f_A(u)du \right) + \sum_{i=n+1}^{n+k} \left(\frac{W_{drawn}}{2} \int_{SCX_i+SCY_i}^{SCX_i+SCY_i+L_{drawn}} f_A(u)du \right)$$

$$corner\_B = \sum_{i=m+1}^{m+k} \left(\frac{L_{drawn}}{2} \int_{SCX_i+SCY_i}^{SCX_i+SCY_i+W_{drawn}} f_B(u)du \right) + \sum_{i=n+1}^{n+k} \left(\frac{W_{drawn}}{2} \int_{SCX_i+SCY_i}^{SCX_i+SCY_i+L_{drawn}} f_B(u)du \right)$$

$$corner\_C = \sum_{i=m+1}^{m+k} \left(\frac{L_{drawn}}{2} \int_{SCX_i+SCY_i}^{SCX_i+SCY_i+W_{drawn}} f_C(u)du \right) + \sum_{i=n+1}^{n+k} \left(\frac{W_{drawn}}{2} \int_{SCX_i+SCY_i}^{SCX_i+SCY_i+L_{drawn}} f_C(u)du \right)$$

Equation 4 Integral form of equations for calculating corner effects

There are assumed to at most k corners and that k will always be less than or equal to four. This has to do with how a corner is selected in the case where there is more than one corner near an active region corner, as is explained below. The sum from m+1 to m+k is due to the assumption that a corner only effects the last segment, m. The corner effect integral is then computed along the width. Similarly, the sum from n+1 to n+k means that only the nth segment is considered and the corner effect is calculated as integral along the length.

For the case where there are more than two well corners near an active region corner (corners 1 and 2 in the example), only one need be included in the corner calculations. The recommended criteria for selecting which corner to use in the corner calculations is pick the one whose value of SCX + SCY is the smallest. For example, if SCX1 + SCY1 < SCX2 + SCY2, then use corner 1.

$$corners\_A = SC_{ref}^{2}\left[\begin{array}{l} \displaystyle\sum_{i=m+1}^{m+k}\left(\frac{W_{drawn}}{2}\left(\frac{1}{SCX_i + SCY_i} - \frac{1}{SCX_i + SCY + L_{drawn}}\right)\right) + \\ \displaystyle\sum_{i=n+1}^{n+k}\left(\frac{L_{drawn}}{2}\left(\frac{1}{SCX_i + SCY_i} - \frac{1}{SCX_i + SCY + W_{drawn}}\right)\right) \end{array}\right]$$

Equation 5 Closed form solution to corners_A equation

$$corners\_B = \left[\begin{array}{l} \displaystyle\sum_{i=m+1}^{m+k}\left(\begin{array}{l} \frac{W_{drawn}}{2}\left(\frac{SCX_i + SCY_i}{10} + \frac{SC_{ref}}{100}\right)\exp\left(-10\frac{SCX_i + SCY_i}{SC_{ref}}\right) - \\ \frac{W_{drawn}}{2}\left(\frac{SCX_i + SCY_i + L_{drawn}}{10} + \frac{SC_{ref}}{100}\right)\exp\left(-10\frac{SCX_i + SCY_i + L_{drawn}}{SC_{ref}}\right) \end{array}\right) + \\ \displaystyle\sum_{i=n+1}^{n+k}\left(\begin{array}{l} \frac{L_{drwan}}{2}\left(\frac{SCX_i + SCY_i}{10} + \frac{SC_{ref}}{100}\right)\exp\left(-10\frac{SCX_i + SCY_i}{SC_{ref}}\right) - \\ \frac{L_{drawn}}{2}\left(\frac{SCX_i + SCY_i + W_{drawn}}{10} + \frac{SC_{ref}}{100}\right)\exp\left(-10\frac{SCX_i + SCY_i + W_{drawn}}{SC_{ref}}\right) \end{array}\right) \end{array}\right]$$

Equation 6 Closed form solution to corners_B equation

$$
corners\_C = \left[\begin{array}{l}
\sum_{i=m+1}^{m+k} \left(\begin{array}{l}
\frac{W_{drawn}}{2}\left(\frac{SCX_i + SCY_i}{20} + \frac{SC_{ref}}{400}\right)\exp\left(-20\frac{SCX_i + SCY_i}{SC_{ref}}\right) - \\
\frac{W_{drawn}}{2}\left(\frac{SCX_i + SCY_i + L_{drawn}}{20} + \frac{SC_{ref}}{400}\right)\exp\left(-20\frac{SCX_i + SCY_i + L_{drawn}}{SC_{ref}}\right)
\end{array} \right) + \\
\sum_{i=n+1}^{n+k} \left(\begin{array}{l}
\frac{L_{drqwn}}{2}\left(\frac{SCX_i + SCY_i}{20} + \frac{SC_{ref}}{400}\right)\exp\left(-20\frac{SCX_i + SCY_i}{SC_{ref}}\right) - \\
\frac{L_{drawn}}{2}\left(\frac{SCX_i + SCY_i + W_{drawn}}{20} + \frac{SC_{ref}}{400}\right)\exp\left(-20\frac{SCX_i + SCY_i + W_{drawn}}{SC_{ref}}\right)
\end{array} \right)
\end{array} \right]
$$

Equation 7 Closed form solution to corners_C equation

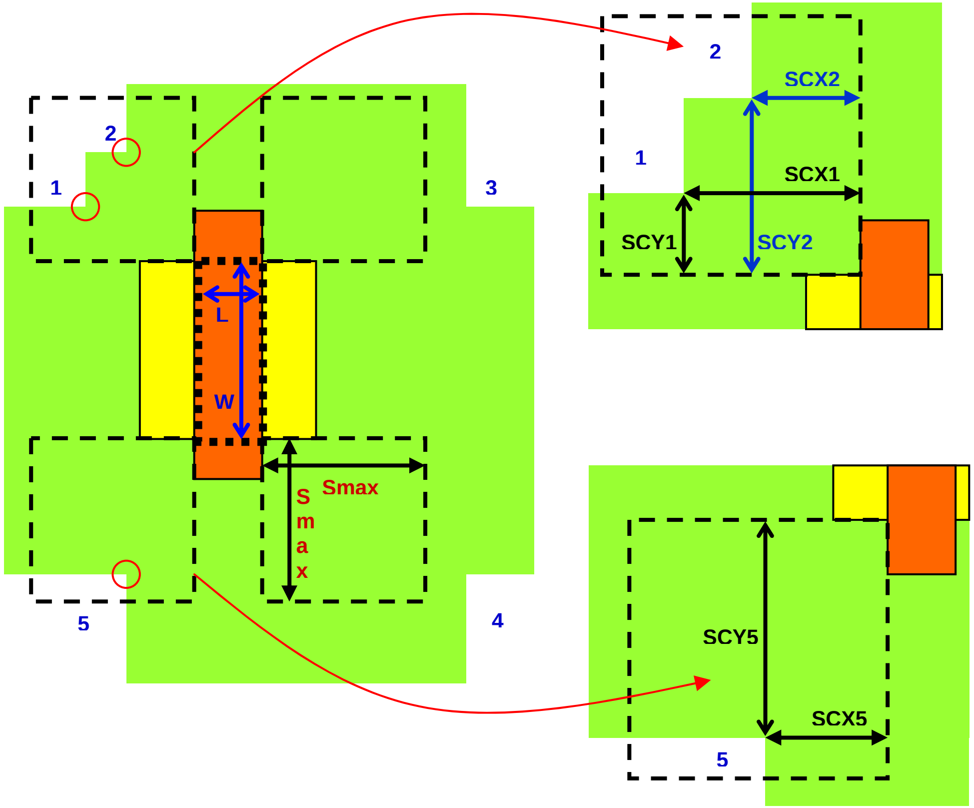

Figure 3 Example layout for corner term calculations

3.4 Parameter extraction for non-rectangular gates

For the case of non-rectangular gates, fracturing of the channel region will be a function of both the gate geometry as well as the well shape. An example of this is shown in Figure 4 (horizontal projections) and Figure 5 (vertical projections). Note that for the shape shown, both sets of projections will have to be performed and included in the calculation of SCA, etc.

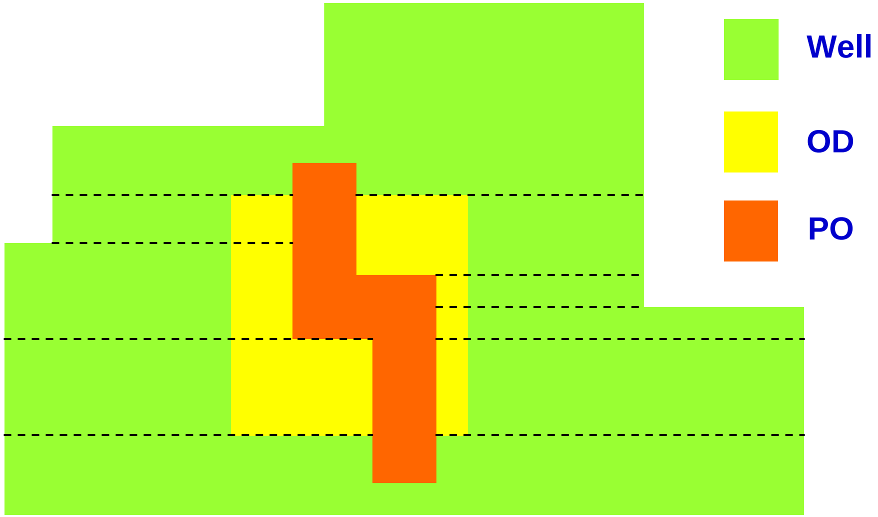

Figure 4 Example of horizontal fracturing for a bent gate

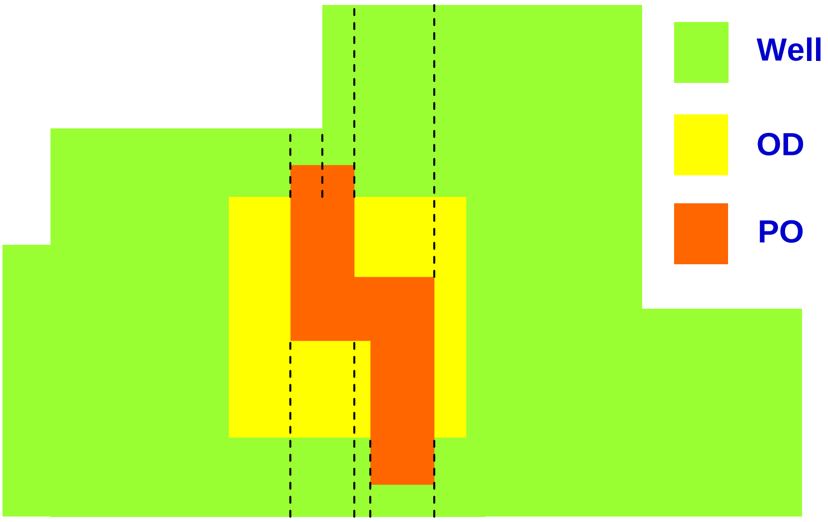

Figure 5 Example of vertical fracturing of a bent gate

3.5 Extracting parameters for multi-fingered devices

Extracting well proximity parameters for a multi-fingered device such as the one shown in Figure 6 is more complex than for a single device.

The recommended method for extracting device parameters for a multi-fingered device is to netlist each finger as a separate device. The standard well scattering calculations should be used on each finger as if each is an independent device. I.e. SCA, SCB, etc. should be determined by measuring distances from the edge of each “devices” channel to the well edge as was done for the single transistor case. In the example figure, each finger (E, F, G and H) should be netlisted as a separate device. For device E, the horizontal projection parameters shown should be extracted and used in the standard calculations for SCA, etc. Note that for clarity, the vertical projection parameters are not shown but the same methodology applies.

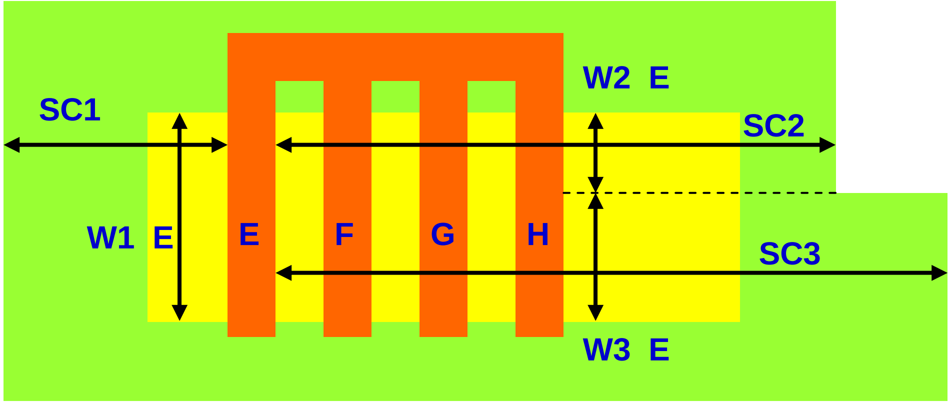

Figure 6 For multi-fingered device, each finger should be extracted as a separate device, each with its own WPE parameters.

It is also possible to average the well proximity parameters and netlist a single device with NF set to the number of fingers and SCA, etc. are represented by the average for each finger. For this example;

- NF = 4
- SCA = (SCA_E + SCA_F + SCA_G + SCA_H)/4
- SCB = (SCB_E + SCB_F + SCB_G + SCB_H)/4
- SCC = (SCC_E + SCC_F + SCC_G + SCC_H)/4

4 Estimation of pre-layout well proximity parameters

In order to estimate well proximity effects before physical layout is complete, its necessary to provide some information about how close the channel region may be to a well edge (Figure 7). While this value is only an estimate, using the minimum allowable distance to the well edge will result in a conservative estimate for well proximity effects. Here, SC is defined as the distance to the nearest well edge. This value will be used in computing SCA, SCB and SCC as shown in Equation 8.

$$\mathrm{SCA} = \frac{{SC_{ref}}^{2}}{W_{drawn}} \cdot \left(\frac{1}{SC} - \frac{1}{SC + W_{drawn}} \right)$$

$$\mathrm{SCB} = \frac{1}{W_{drawn} \cdot SC_{ref}} \left(\begin{array}{l} \dfrac{SC_{ref}}{10} \cdot SC \cdot \exp\left(-10 \cdot \dfrac{SC}{SC_{ref}} \right) + \dfrac{{SC_{ref}}^{2}}{100} \exp\left(-10 \cdot \dfrac{SC}{SC_{ref}} \right) \\ -\dfrac{SC_{ref}}{10} \cdot \left(SC + W_{drawn} \right) \cdot \exp\left(-10 \cdot \dfrac{SC + W_{drawn}}{SC_{ref}} \right) \\ -\dfrac{{SC_{ref}}^{2}}{100} \exp\left(-10 \cdot \dfrac{SC + W_{drawn}}{SC_{ref}} \right) \end{array} \right)$$

$$\mathrm{SCC} = \frac{1}{W_{drawn} \cdot SC_{ref}} \left(\begin{array}{l} \dfrac{SC_{ref}}{20} \cdot SC \cdot \exp\left(-20 \cdot \dfrac{SC}{SC_{ref}} \right) + \dfrac{{SC_{ref}}^{2}}{400} \exp\left(-20 \cdot \dfrac{SC}{SC_{ref}} \right) \\ -\dfrac{SC_{ref}}{20} \cdot \left(SC + W_{drawn} \right) \cdot \exp\left(-20 \cdot \dfrac{SC + W_{drawn}}{SC_{ref}} \right) \\ -\dfrac{{SC_{ref}}^{2}}{400} \exp\left(-20 \cdot \dfrac{SC + W_{drawn}}{SC_{ref}} \right) \end{array} \right)$$

Equation 8 Calculation of SCA, SCB, and SCC for pre-layout devices

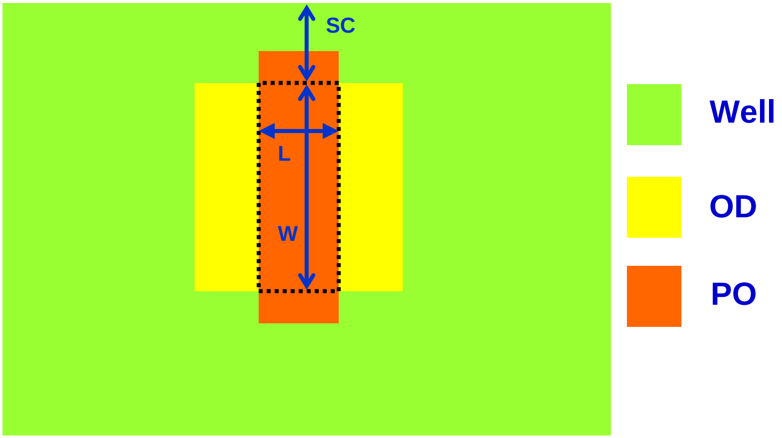

Figure 7 Approximation of SCA, SCB, and SCC for pre-layout simulation using an estimated value for SC

For the case of multi-fingered devices its still necessary to assume that there is only one well edge close to the device, as shown in Figure 8. SCA, SCB and SCC would then be calculated using Equation 8.

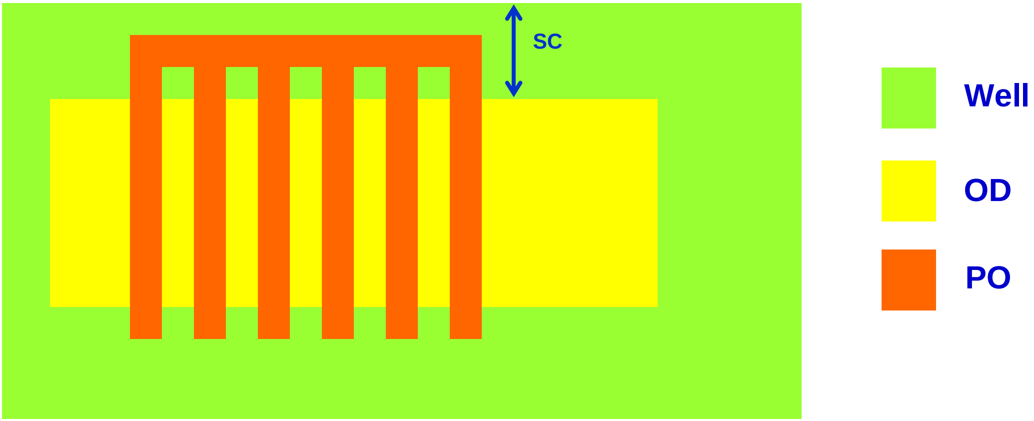

Figure 8 Approximation of well proximity effects using an estimated SC for multi-fingered devices.

5 References

[1] T. B. Hook, et al., IEEE Trans. on Electron Devices, Vol. 50, Sept. 2003, pp. 1946-1951.